The A. & M. College of Texas

Department of

OCEANOGRAPHY AND METEOROLOGY

Research Conducted Through The

Texas A.&M. Research Foundation

College Station, Texas

INFLUENCE OF VERTICAL MOTION ON THE SAVONIUS ROTOR CURRENT METER

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Department of Oceanography and Meteorology
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I. INTRODUCTION

The Office of Naval Research has been supporting general investigations of the Savonius rotor current meter for the past two years under contract Nonr 2119(4) at the A. & M. College of Texas. Most of the experimentation has been done at the Hytech tow tank in close cooperation with James M. Snodgrass of Scripps Institution of Oceanography (also under ONR contract) and Donald J. Cretzler of Hytech Division of Bissett-Berman Corporation. The work reported herein is largely based on these studies as supplemented by a series of special tests using equipment provided by the U. S. Public Health Service under contract RO-V2165-63.

At the time the contract was initiated, PHS was considering several alternative data systems employing the Savonius rotor to gather circulation data in the Great Lakes. The various Savonius rotor meters now on the market use the same rotor but details of the rotor housing vary widely and some of these have been shown to significantly affect performance of the transducer. Therefore, the results given in this report strictly are applicable only to the particular models tested. However, in the interest of providing a reasonable estimate of the actual problem confronting PHS in their limnological survey, discussion (and often conjecture) is pointed to the probable relation of these results to the operation of the specific current meter recently selected by PHS; namely, the so-called Richardson meter manufactured by Geodyne Corporation.

The scope of the PHS interest under this contract was the influence of vertical motion on the Savonius rotor current meter. This report, however, embraces several other aspects of meter performance derived from the ONR-Hytech supported work that seem pertinent to the PHS application and some of which need discussion for proper interpretation of the vertical motion results.

II. THE TEST FACILITY

Gaul (1962b) summarized calibration work that had been done with various Savonius rotor current meters during the period from development of the first meter by Snodgrass (1955) to the end of 1961. The earlier tests were performed at the Convair tow tank in San Diego, in swimming pools and in specially built "slosh tanks" (Marine Advisers, 1960). Only test data taken at the Hytech tow tank during 1961-1962 are considered in this report because most of the earlier tests were repeated in greater detail and with more experimental control.

The Hytech tow tank facility (Fig. 1) has been described and evaluated from the standpoint of calibrating Savonius rotor current meters (Gaul, 1961). The fresh water tank is unlined concrete 150 feet long and nominally 7 feet wide by 6 feet deep. The tow carriage is equipped with ball bushings that ride on precision ground rails mounted on the tank walls. The rails are at the same elevation within ± 1/8 inch over their entire length and are closely aligned to avoid binding with the rubber cushioned ball bushings. The drive system consists of a variable speed hydraulic pump and motor combination coupled with sheaves and worm gear drive to a continuous loop high tension steel cable attached to the carriage.

A point of major concern in these tests has been variability of the carriage speed. The nature of the rotor as an omnidirectional integrator is such that output, especially at low speeds, may be affected significantly if the carriage speed is not steady and the amount of influence depends on the instrument response (about which little is quantitatively known) at the particular mean speeds and speed variations involved. Great pains have been taken to minimize carriage speed variability and it is believed to be acceptably low at mean speeds above 0.05 knots.

A second possible problem is that of tank wall and bottom effects and circulation caused by movement of the instrument. On one occasion a very sensitive rotor system was able to detect water movements for more than 30 minutes after the carriage was stopped at the end of a run at about 0.3 knots. Whether these pulsations were caused by meter induced circulation or free inertial waves traveling between the end walls is uncertain. The tank was allowed to "settle" for 30 minutes to several hours between low speed runs (0.05

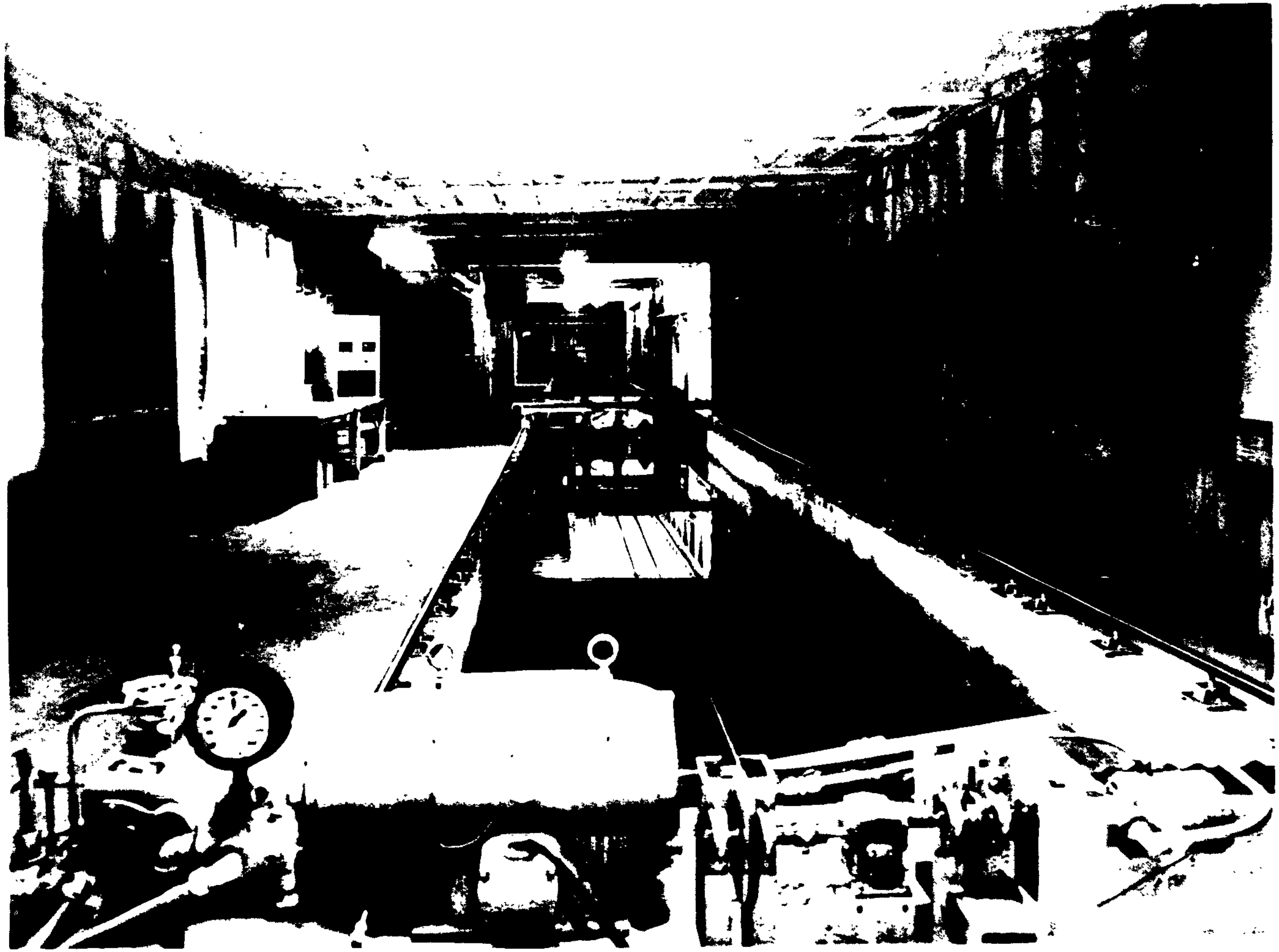

Fig. 1. Hytech tow tank facility.

to about 0.2 knots); in no case was a run made within 15 minutes of the previous run and successive runs were made at increasing speeds. These induced water motions are considered to be the main source of experimental error.

III. EXPERIMENTAL MODELS

Four current meter models are considered in this report. These are denoted T2, CS-2, CS-6 and ST-5. The first three are "off-the-shelf" units manufactured by Hytech and the last is a unit built by J. M. Snodgrass for evaluation comparison with CS-6. The rotor size and configuration is the same for all of the current meters. This is the "standard" that has been used for all commercially available rotor meters and is likewise used in the Geodyne meters purchased by PHS.

Meter T2 (Fig. 2) is the most similar to the Geodyne meters in exterior appearance and physical layout of the case. The six stand-offs are on a 7 3/4 inches diameter bolt circle. Clearance between the top housing plate and the top of the rotor is about 3/4 inch; clearance at the bottom is about 1/2 inch. In all units except ST-5 the bearings are carballoy with 1/8 inch diameter shafts identical to those used by W. S. Richardson (manufactured by John Worley Company). The bearings of meter ST-5 had a 1/4 inch shaft end supported on a pyroceramic ball.

Meters CS-2 (Fig. 3) and CS-3 were identical models. A "spider" configuration is used in place of solid end plates; the stand-offs are 1/4 inch O.D. on a bolt circle of 9 1/2 inches diameter and the pick-up housing is about half the diameter used on meter T2.

Rotor ST-5 was towed in the apparatus shown in Fig. 4. When the meter was towed the vertical part of the "U" support was at 90° to the axis of flow. The magnetic pickup was adjacent to the edge of the bottom plate that contained 24 evenly spaced iron slugs in its periphery. Meters T2, CS-2, and CS-6 were equipped with a 16-tooth interruptor that passed beneath the pick-up head positional above the rotor.

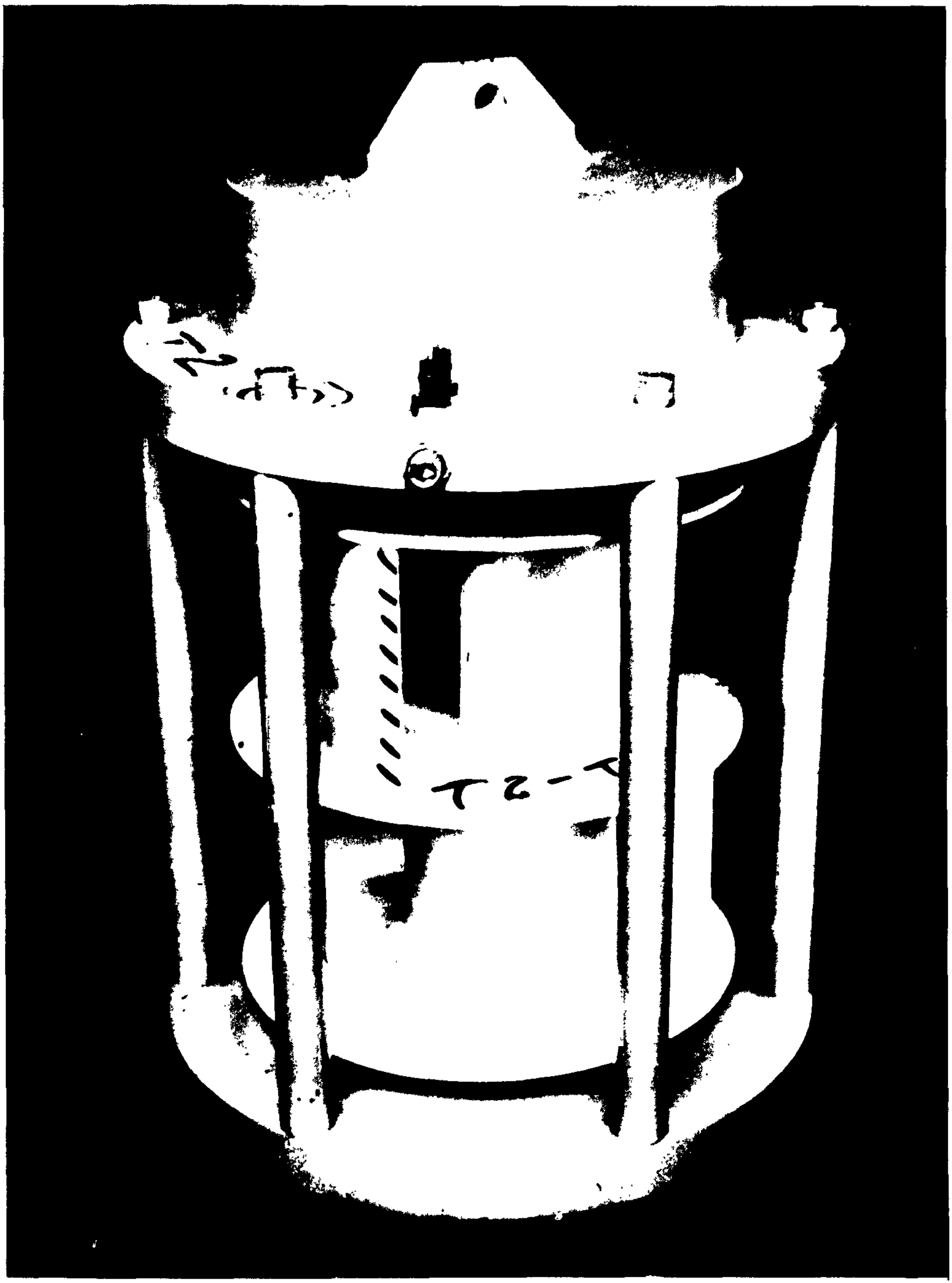

Fig. 2. Test meter T2.

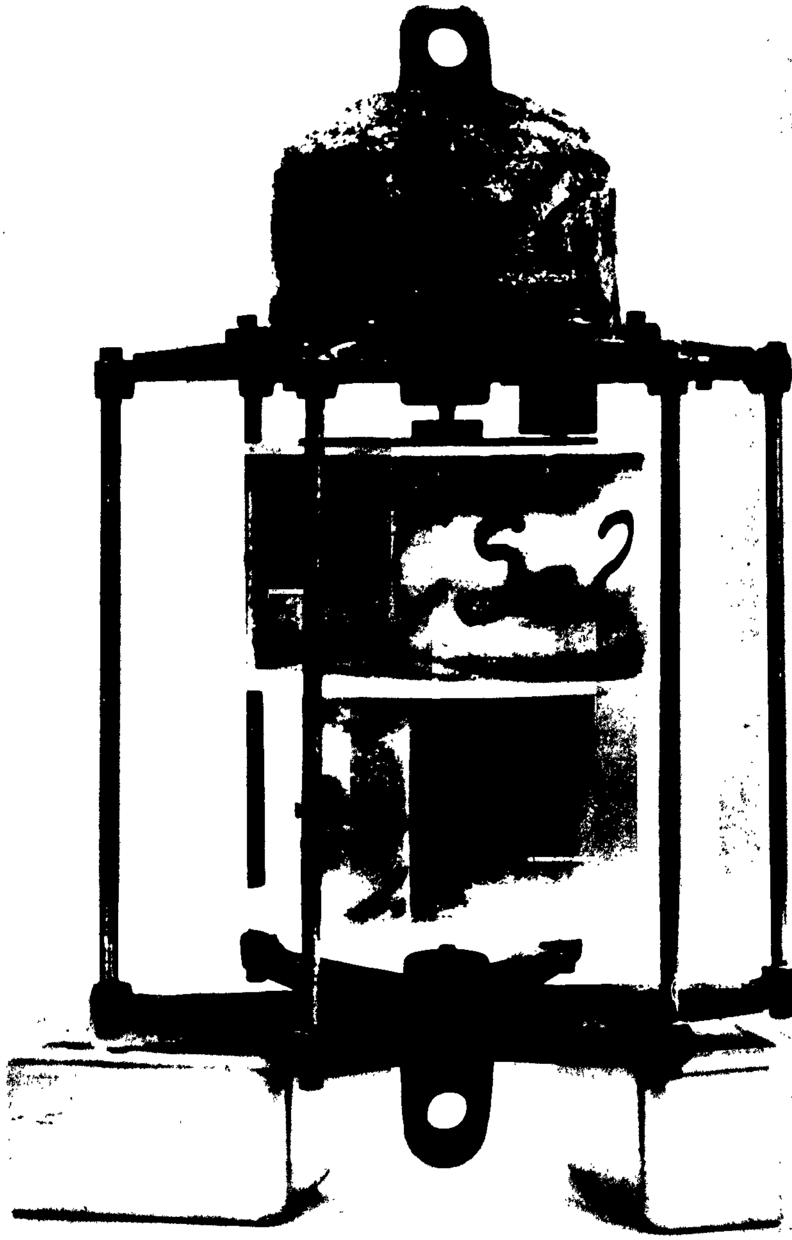

Fig. 3. Test meter CS-2.

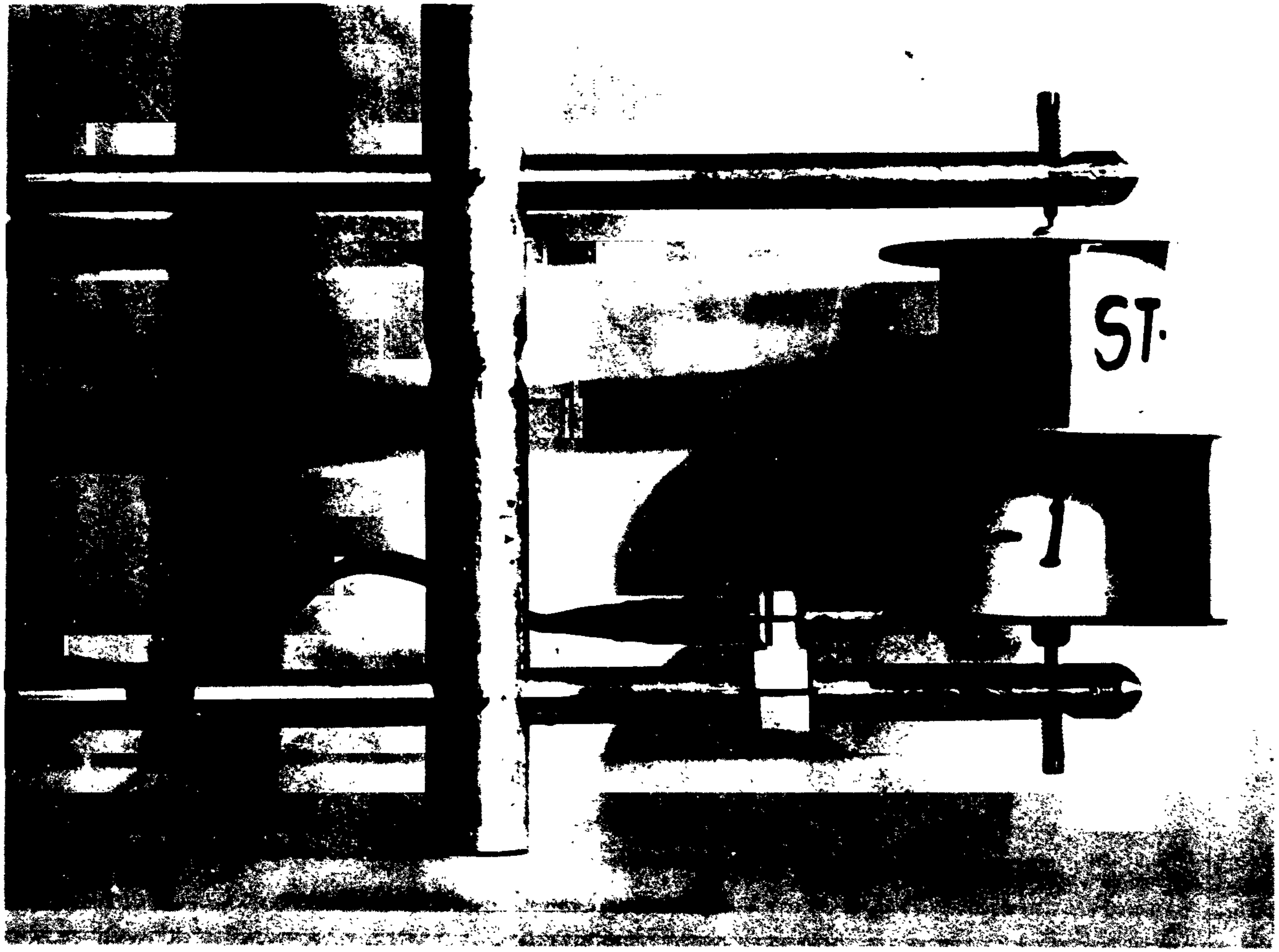

Fig. 4. The support assembly used for rotor ST-5.

IV. THRESHOLD

The threshold of a current meter, i.e., the minimum current speed it is capable of detecting, is of major importance. Unfortunately the Savonius rotor has no clearcut threshold that fits this definition because the rotor turns non-uniformly at low speed due to a dependence on orientation of flow relative to rotor vanes (Savonius, 1931). As the rotor gains momentum, once it is clearly above the threshold of the lowest torque position, the rotational speed rapidly becomes more uniform. It is rather difficult, in the presence of tow carriage speed variations and residual turbulence in the tank, to accurately establish a threshold value. With good bearings, clean surfaces and moderate manufacturing care the threshold for all torque positions should be within or below the range of 0.02 to 0.05 knots and, for practical purposes, the operating threshold may be taken at 0.05 knots.

V. STEADY STATE CALIBRATION

Reference is made to Gaul (1962b) for a detailed description of calibration procedure and results for meter T2, and to Gaul, Snodgrass and Cretzler (1963) for information on CS-2. Units CS-6 and ST-5 were used for the test series of November 1962 and the results are discussed below.

In the earlier tests the procedure for obtaining steady state data was to record rotor output during a segment of the total run only. The particular part of the run selected for recording was arbitrary depending mostly on the practical aspects of timing, marking records, etc. At first the run was commenced only a few revolutions after the carriage was started. As experience began to show that reproducibility was low, a greater travel distance was allowed before commencing a recording and finally recordings were made from start to finish. This enabled uniform selection of record segments by the data analyst to improve the consistency of results and comparability between runs.

Fig. 5 gives the best estimate of the steady state output of each of the 3 rotors tested in July or November 1962. These are for the rotor towed in <u>still</u> water with the axis <u>vertical</u>. That rotor efficiency might depend on turbulent characteristics of flow past it was first suggested by Savonius (1931) who found that a rotor used for a wind power generator operated about 15% faster in the natural wind than in a wind tunnel. This aspect of current meter rotors is as yet uninvestigated.

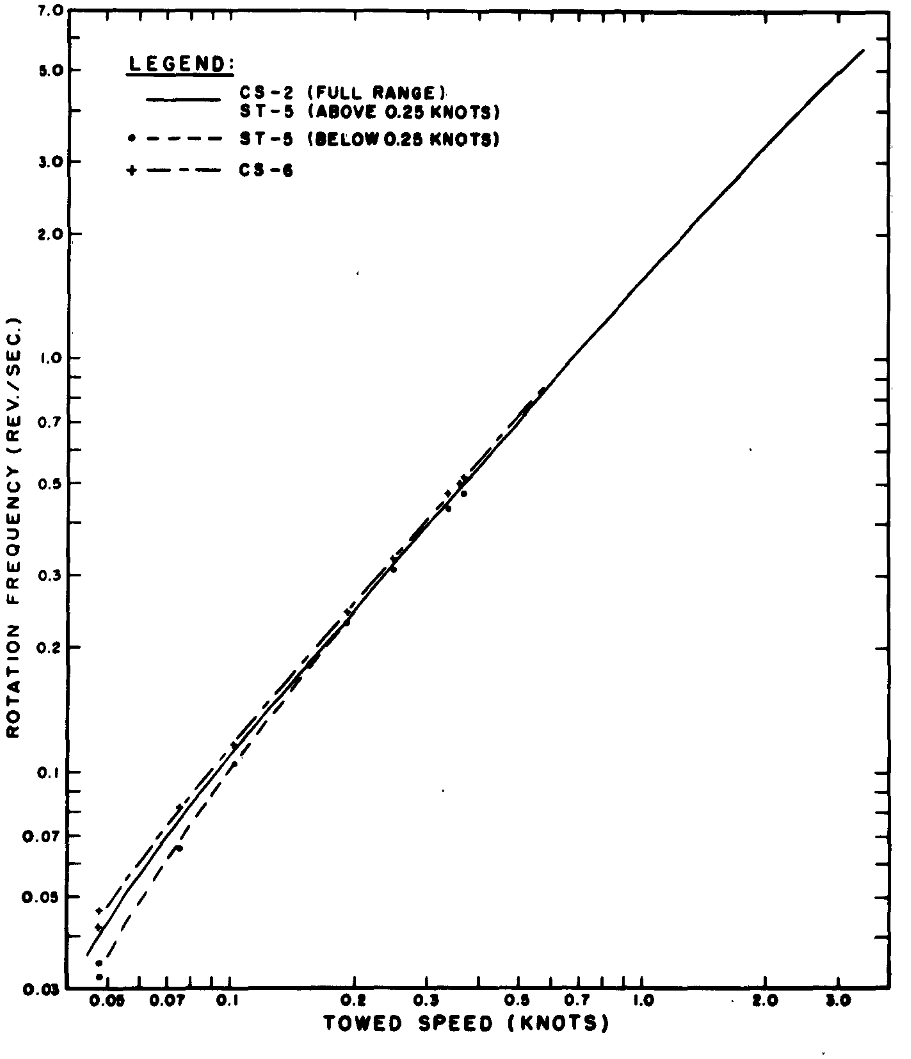

Fig. 5. Comparative steady state calibration curves for rotor test models.

The meters were mounted rigidly on the tow carriage to keep them vertical and motionless relative to the carriage. In some of the tests a single meter was towed and in others two were towed in tandem. Gaul (1961) found no detectable difference in meter performance under these two conditions.

The curve of CS-2 is based on 60 runs and those of CS-6 and ST-5 on about 50 runs. The calibration of CS-2 was generally derived from rotor outputs averaged over 5 to 10 revolutions at an unknown number of revolutions after the run was begun. The outputs of rotor CS-6 and ST-5 were uniformly averaged over 15 revolutions beginning with the sixth revolution after the run was commenced. The original data for the CS-6 and ST-5 steady state runs with axis vertical are summarized in Appendix A.

VI. INFLUENCE OF STAND-OFF RODS

The Richardson meters use relatively large stand-off rods compared to the 1/4 inch O.D. rods in the Hytech model 364 meter. Also, the clearance between these larger rods and the rotor is less than 1 inch. Therefore, the rods, as turbulence generators and energy absorbers, may detract from the operational similarity of the different models.

Tests have been performed to investigate the possible influence of stand-off rods on meter performance. Meter T2 (Fig. 2) was first calibrated with 5/8 inch O.D. stand-offs and then with 3/8 inch O.D. rods. The results are shown in Fig. 6. Although the number of runs is limited, the differences between the smooth curves are believed to at least qualitatively show that the 1/4 inch increase in the O.D. of the stand-offs significantly reduced rotor efficiency. In this particular case, the reduction is in the region of 5% to 10%.

VII. INFLUENCE OF TILT

Rotors CS-6 and ST-5 were towed during the November 1962 experiments with the normally vertical axis tilted in the vertical plane of flow. The experimental procedure and data analysis was identical to that of steady state runs with the rotor axis vertical. The tilt angle, α, was taken as positive when the leading edge of the rotor was tilted up from the flow axis and negative when the leading edge was down.

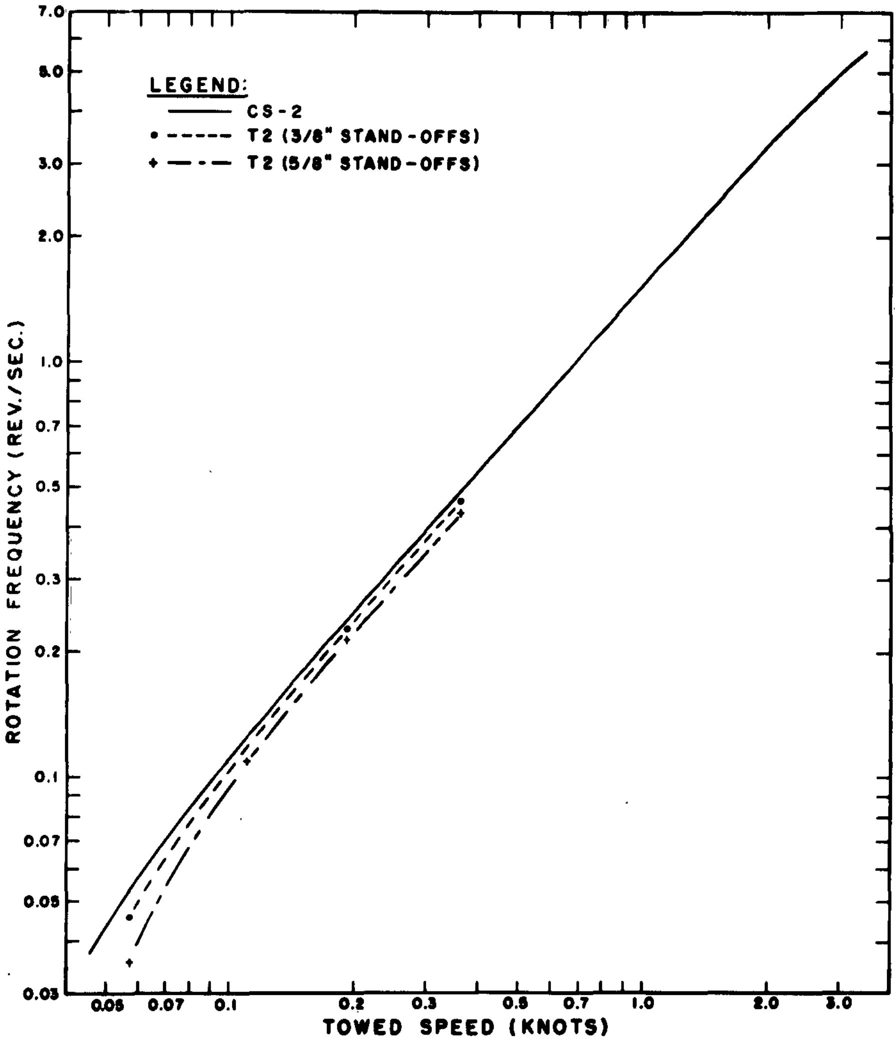

Fig. 6. Calibration curves for meter T2 with 3/8" and 5/8" stand-offs.

Tilt angles of 10, 15, 20 and 30 degrees were used for steady speeds of 0.115 knots and 0.74 knots. The data are summarized in Appendices B and C. The ratio of rotation frequency, f_α, with the rotor tilted to rotation frequency, f_s, with the rotor axis vertical is given as a function of tilt angle, α, for rotors CS-6 and ST-5 in Figs. 7 and 8 respectively. The values of f_s were taken from the calibration curves in Fig. 5.

Several features of the results shown in Figs. 7 and 8 deserve particular attention. First, the influence of tilt is distinctly different for positive and negative angles. In terms of field operation it should be noted that a submerged buoy system such as used by Gaul (1962a) will introduce a positive tilt angle in the presence of a current whereas a negative tilt angle will normally be introduced by a slack or semi-taut surface flotation system.

Secondly, the tilt effect is definitely dependent on the current speed. Only 2 speeds in the low end of the operational range of the rotor were selected for the experiments. Differences in the curves obtained are significant enough (5% to 10%) to merit further experiments over a wider range of speeds. Furthermore, the results obtained deviate markedly (up to 20%) from a dependency on the cosine of the tilt angle.

Also significant is the difference between results obtained with CS-6 and ST-5. This indicates that the meter case appurtenances are of major importance in modifying flow to which the rotor responds. The case configuration of the Richardson meters being used by PHS is quite different from that of CS-6 so the effect of tilt will likely be significantly dissimilar.

VIII. SURFACE ROUGHNESS

One of the most pertinent and least investigated aspects of current measurement is the degree that meter performance is affected by altering surface roughness, especially with marine fouling. The nature of biological fouling precludes very definite or quantitative answers but orders of magnitude are important. Prior to the experiments at Hytech in July, a meter of the same design as CS-2 was suspended in San Diego Bay for about 4 weeks. It accumulated a very even coat of natural fouling less than 1/8 inch thick that was left undisturbed for part of the calibration experiments.

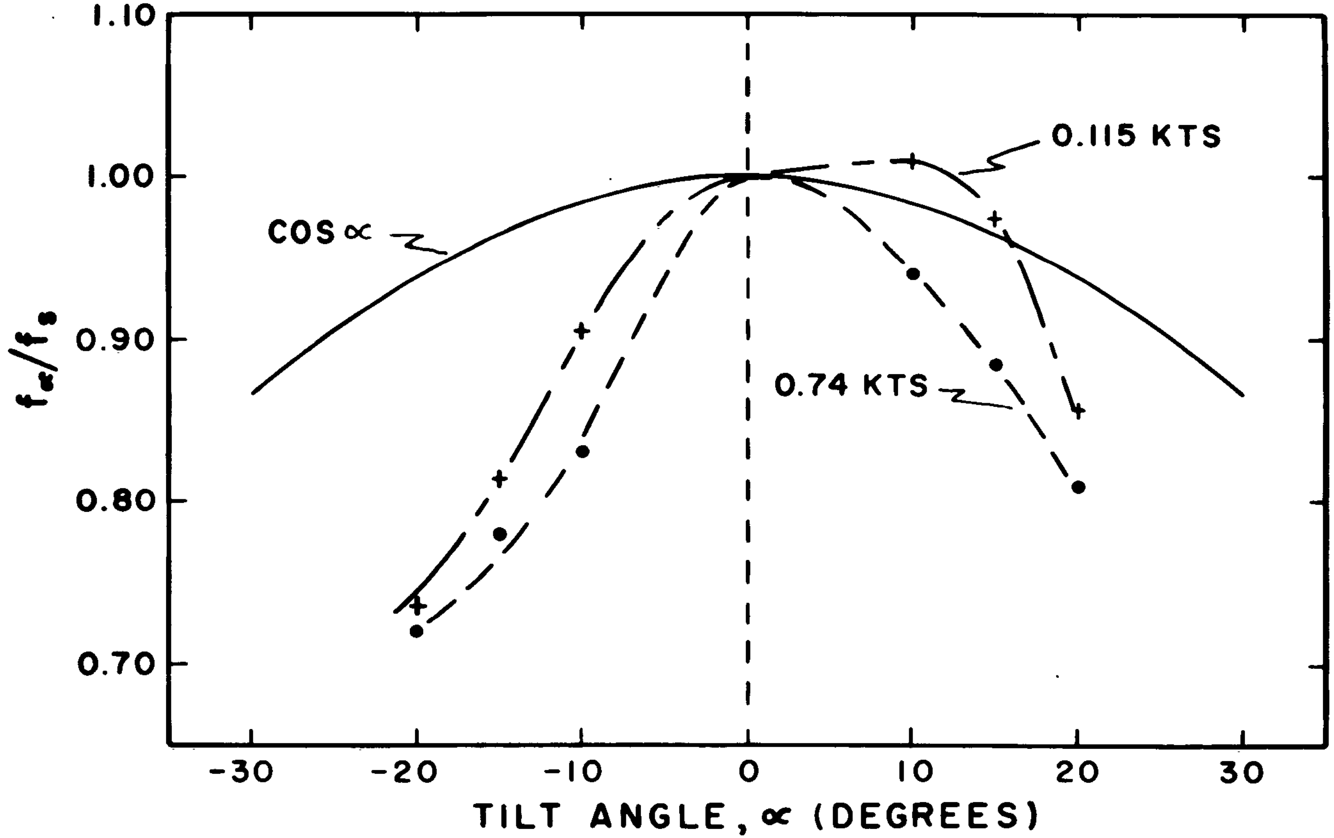

Fig. 7. Influence of tilt on output of rotor CS-6.

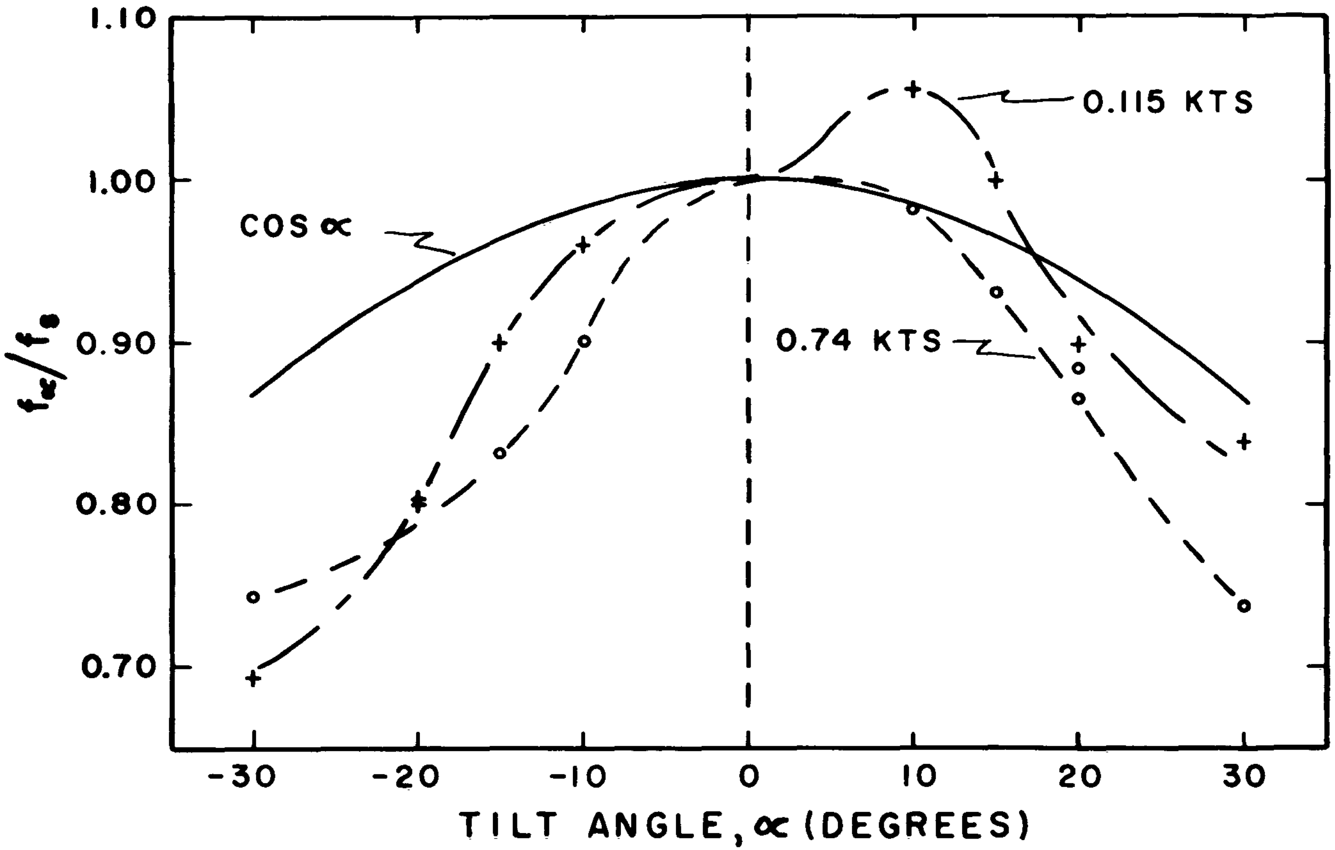

Fig. 8. Influence of tilt on output of rotor ST-5.

The results of the calibrations are discussed by Gaul, Snodgrass and Cretzler (1963). The thin coat of fouling caused a 40% reduction in rotor efficiency at 0.25 knots. It was further indicated that the fouled rotor operated more efficiently at low speeds and its threshold speed was at a lower speed. It seems probable that the degree of fouling and slime accumulation likely to be encountered in the Great Lakes environment, especially over long periods of immersion, may seriously degrade rotor performance.

IX. RESPONSE

Several approaches have been made to determination of meter response to acceleration and deceleration. Until recently, little thought was given to employing the "distance constant" concept that is applied in anemometry rather than the more common "time constant." Gaul, Snodgrass and Cretzler (1963) presented results of response tests using a near-step change between zero and a steady speed. This is probably realistic when the step is positive, i.e., acceleration from zero to a steady speed. However, when the movement of the meter through the water is suddenly stopped, the behavior of the device is definitely not comparable to its performance when both of the speeds are above zero, as has been suggested by Stevens and Shodin (1963).

During the tests in November 1962, a series of runs were made in which several speed changes were introduced during each run. Steps were both positive and negative. The steps were arranged in a variety of magnitudes and are summarized in Appendix D. Average times required for 63% and 95% responses are tabulated in Table I. These were obtained from smooth curve fits of average response values calculated from pulse intervals originally recorded. These values are probably not accurate to much better than $\pm$ 10% because the actual speed change only approximates a step and because the reading resolution on the recorded strip charts was usually poor. Under these circumstances the times for response given in Table I in all instances are more than would be found for true step changes such as might be attained with the method of Stevens and Shodin (1963). Also given in Table I are values for the distance constant, S_{63}, which were calculated from

$$S_{63} = 1.69 u_2 \tau$$

where u_2 is speed in knots after the step change and τ is the time in seconds required for 63% response.

TABLE I

RESULTS OF RESPONSE TESTS FOR METER CS-6, NOVEMBER 1962

No. of runs	Avg. Speed (kts.)	Step Change (kts.)	t_{63} (sec.)	t_{95} (sec.)	S_{63} (ft.)
1	0.025	0.05	3.5	15.0	2.95
1	0.04	0.08	1.8	7.0	2.45
1	0.095	0.19	1.6	7.5	5.15
4	0.12	0.24	1.2	4.2	4.85
1	0.18	0.36	1.3	5.0	7.9
1	0.19	-0.11	3.6	8.5	8.2
1	0.25	-0.23	3.2	8.5	7.35
2	0.25	-0.17	2.6	6.5	7.5
1	0.27	0.47	1.2	2.0	10.2
1	0.30	0.11	1.1	1.7	6.7
1	0.34	-0.34	2.4	6.0	7.0
2	0.42	-0.17	1.2	3.4	6.85
1	0.63	-0.23	0.8	1.5	6.9

From the results given in Table I, the following general features are discernible. The time constant for a positive change from zero speed decreases as the magnitude of the change increases, varying from about 4 seconds near the threshold to about 1 second for a half-knot step. The "distance constant" does not appear to be constant but instead is shorter at low speeds. Although the data are poor, it probably is reasonable to conclude that this parameter does approach a constant value in the neighborhood of 6 to 10 feet at current speeds above 0.2 knots. It is probable, further, that the time and/or distance constants will depend somewhat on the magnitude of current speed changes, particularly as the low speeds approach zero.

Fig. 9 gives the speed indicated by the rotor as it is subjected to irregular current (towed) speed variations. Some of the characteristic response features described above are readily discernible. Note that when the speed varied almost sinusoidally with a period of

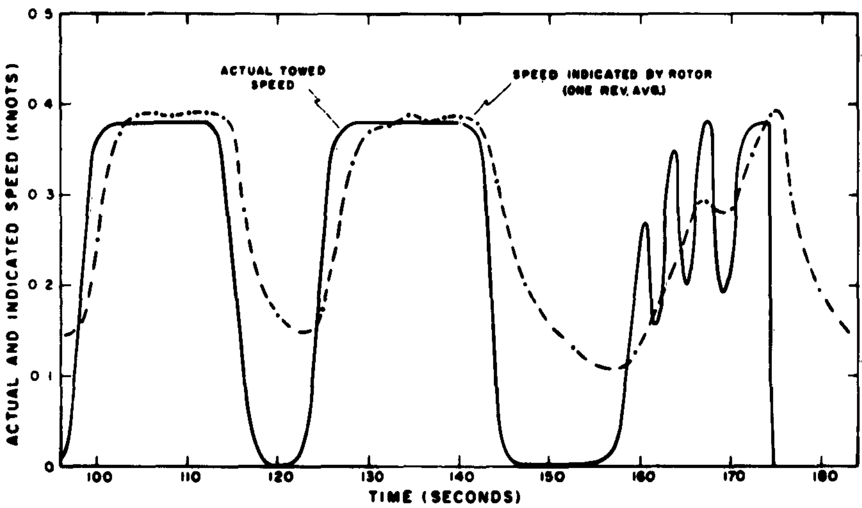

Fig. 9. Response of rotor CS-2 to irregular changes in tow carriage speed.

roughly 4 seconds (between elapsed times of 160 to 170 seconds), the indicated speed followed the mean trend but failed to indicate the variations. The plotted points are based on single rotor revolution averages; somewhat better frequency resolution might have been obtained by shorter averages.

X. INFLUENCE OF VERTICAL MOTION

For the vertical motion experiments an electric-driven counterbalanced rocker-arm oscillator was set up on the tow carriage. Such an arrangement gives a time-displacement oscillation that is slightly distorted from a true sinusoid but the amount of distortion (less than 2%) is considered insignificant relative to the output variability of the rotors. The rocker arm was coupled to 2 vertical rotor mounting rods which were driven in unison through ball bushing guide sleeves.

Total displacements (heights) of 1 and 2 feet were used with periods (for complete cycles) of 5, 10, 15 and 20 seconds. Each combination of height and period was run at a constant towed speed of 0.116 and 0.735 knots. Rotors CS-6 and ST-5 were used in all runs. The data are summarized in Appendix E.

In Figs. 10 and 11 are plotted rotor outputs for runs made with heights of 2 feet and 1 foot respectively at a constant speed of 0.116 knots and an oscillatory period of 20 seconds. The rotor outputs have been converted to indicated current speed using the appropriate calibration curve in Fig. 5. The plotted points represent one-quarter revolution averages. The smooth curves drawn through the data points are freehand representations of instantaneous indicated speed; this non-rigorous curve fitting undoubtedly reduces actual variability and somewhat attenuates the peaks and troughs. This is especially true in the case shown in Fig. 12 where the vertical oscillation period was 5 seconds so that only 2 or 3 data points are obtained for each cycle of the oscillator.

Several features are of particular interest in Figs. 10 and 11. It is obvious that the rotor "sees" the vertical component of motion or, more correctly, the vertical motion significantly influences the rotational forces acting on the rotor. Strangely, however, the indicated speed variation has a period half that of the vertical motion. It is equally unexpected that the indicated speeds are conspicuously lower than the actual

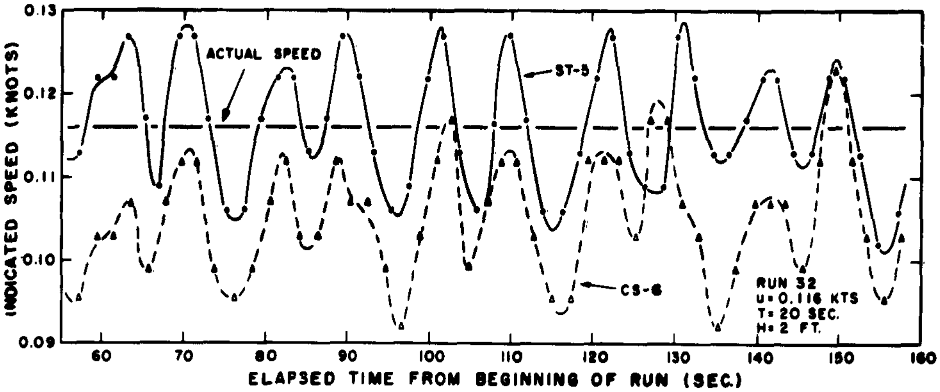

Fig. 10. Speed indicated by rotors for constant speed of 0.116 knots with vertical oscillation of 20 seconds period and 2 feet height.

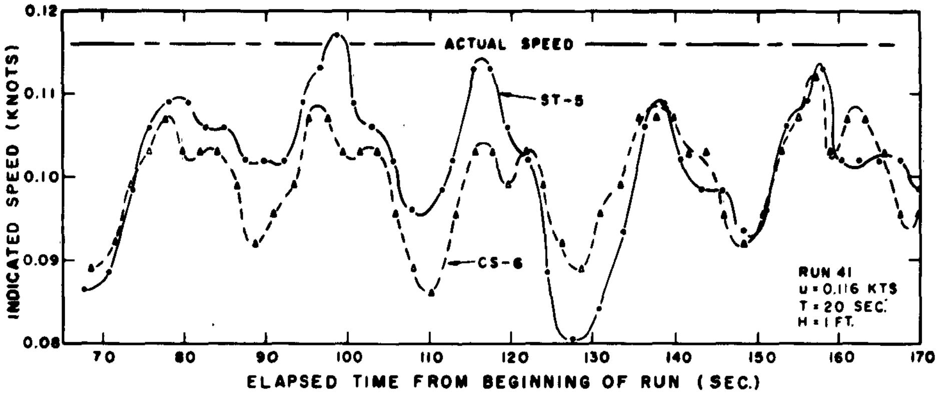

Fig. 11. Speed indicated by rotors for constant speed of 0.116 knots with vertical oscillation of 20 seconds period and 1 foot height.

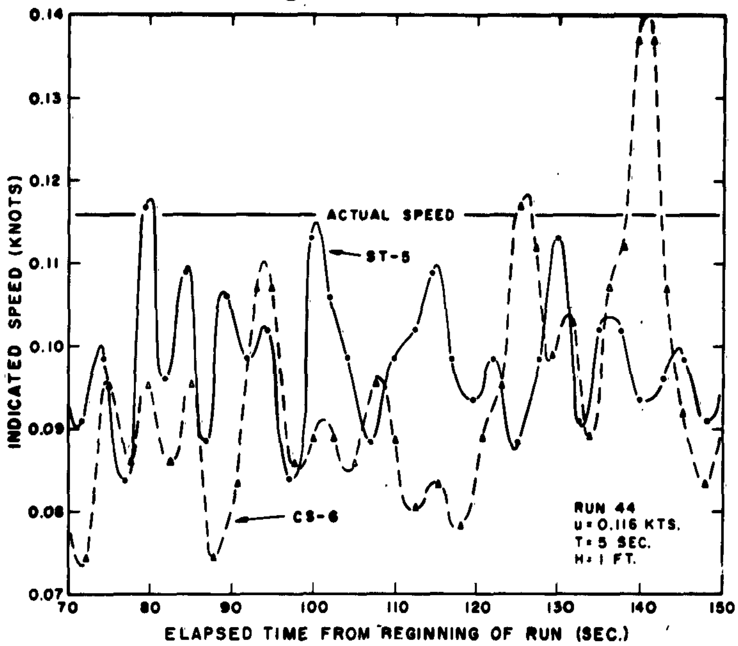

Fig. 12. Speed indicated by rotors for constant speed of 0.116 knots with vertical oscillation of 5 seconds period and 1 foot height.

speed except in the case of rotor ST-5 for the case shown in Fig. 10. Indicated speeds according to both the rotors vary cyclically but ST-5 (completely exposed rotor) operates more erratically and it usually indicates a higher speed.

In Figs. 13 and 14 are shown speeds indicated for heights of 1 and 2 feet respectively at a constant speed of 0.735 knots and an oscillatory period of 5 seconds. Plotted points represent single revolution averages. These curves again exhibit an indicated speed variation at half the period of vertical movement. The magnitude of deviation from a steady speed is less for ST-5 than of CS-6 and at the 1 foot height the variability is within a nominal range of $\pm$ 0.02 knots.

One of the main practical points of interest is the degree to which the vertical motion alters the average rotor output. Normally, the rotor output is averaged in terms of the time required for some fraction or multiple of a rotor revolution. In the presence of a variable rotation rate, the average obtained in this manner should be higher than the average of instantaneous values taken at uniformly spaced increments of time. Given in Appendix E for all runs are mean indicated speeds based on single revolution averages. Also given are time averages for the 3 runs plotted in Figs. 10, 11 and 14. The time increment used was one-tenth of the oscillation period. For these cases the difference between the 2 averaging techniques was insignificant.

There is no clear-cut relationship between the actual and mean indicated speeds except that indicated speeds are generally lower. The average speed indicated by rotor CS-6 was lower than the actual speed for all runs used. This difference amounted to 0.013 (11%) at 0.116 knots and 0.069 (9.4%) at 0.735 knots. Of the 14 runs successfully made with ST-5, 10 gave an indicated speed lower than the actual speed. The average of the difference for these 10 examples of lower indicated speed was 0.011 (9.5%) at 0.116 knots and 0.05 (6.8%) at 0.735 knots. Using all 14 runs the average indicated speed at 0.116 knots is 0.107 and at 0.735 knots it is 0.731.

The standard deviations of indicated speeds for each of the runs was computed. The results are shown in Table II together with actual and average indicated speeds.

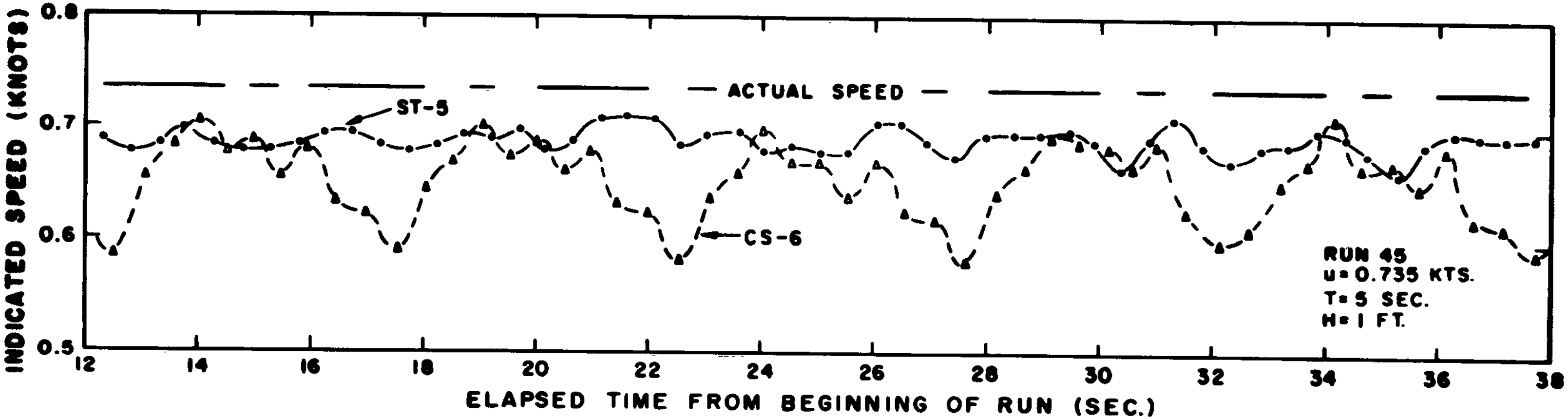

Fig. 13. Speed indicated by rotors for constant speed of 0.735 knots with vertical oscillation of 5 seconds period and 1 foot height.

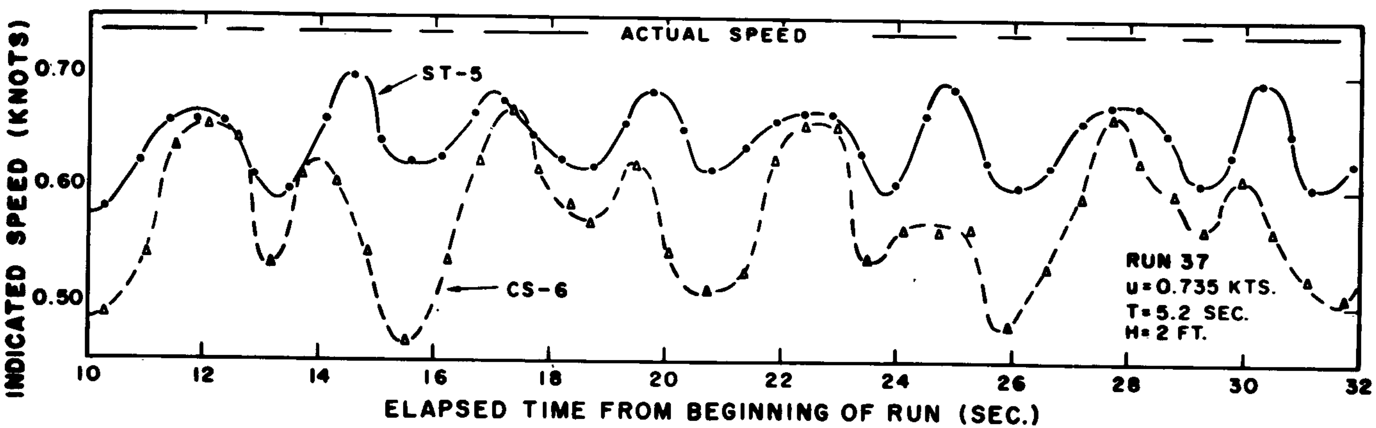

Fig. 14. Speed indicated by rotors for constant speed of 0.735 knots with vertical oscillation of 5.2 seconds period and 2 feet height.

TABLE II

SUMMARY OF ROTOR INDICATIONS
FOR SPEED RUNS WITH VERTICAL OSCILLATION

Actual Speed (kts.)	Osc. Ht. (ft.)	Osc. Period (Sec.)	Rotor CS-6 Ind. Speed (kts.)	Rotor CS-6 Std. Dev. (%)	Rotor ST-5 Ind. Speed (kts.)	Rotor ST-5 Std. Dev. (%)
0.116	1	5	0.096	15	0.099	7
0.116	1	10	0.106	5	0.113	4
0.116	1	15	0.098	5	0.099	6
0.116	1	20	0.100	6	0.102	8
0.116	2	15	0.109	8	0.109	10
0.116	2	20	0.106	7	0.117	6
0.735	1	5	0.653	5	0.689	2
0.735	1	10	0.706	3	0.738	1
0.735	1	15	0.721	4	0.698	2
0.735	1	20	0.719	2	0.744	0.9
0.735	2	5	0.580	9	-----	---
0.735	2	5.2	0.580	10	0.643	10
0.735	2	10	0.647	7	0.709	3
0.735	2	15	0.686	6	0.686	2
0.735	2	20	0.705	4	0.741	2

XI. CONCLUSIONS

With the exception of the plastic rotors, the meters discussed in this report are not the same as those being used by PHS in the Great Lakes. The stand-off rod size is larger on the PHS meters and this should cause slightly less efficient operation than given for meter T2 with 5/8 inch O.D. rods shown in Fig. 6. The calibration curve furnished with the meters should be checked against the curve for 5/8 inch rods in Fig. 6 and if the difference is more than 5% at or above 0.2 knots, it is recommended that a selected group of the meters be recalibrated.

A second major difference in the housing is the size of the plates above and below the rotor. Because of these, the curves given for influence of tilt angle may not apply within ± 5%. Further tilt experiments should be performed over a greater range of speeds; meanwhile, an average of the curves given for CS-6 could probably be

used as a first approximation in currents of 0.1 to 1 knot. It is certain that tilt angles greater than 5° cannot be ignored and the use of a cosine function will result in over ± 10% error at tilt angles greater than 10°.

A realistic threshold for the Savonius rotor instrument is 0.05 knots. From 0.05 to 0.1 knots the indicated current speed should be averaged in multiples of 1 rotor revolution. The steady state calibration is considered accurate to ± 5%. Under ideal field conditions the nominal accuracy of the meter is probably not much better than ± 10%. The effect of natural turbulence on meter performance remains unknown.

Marine fouling has a marked effect on rotor output, even when not very severe. The rotors should either be kept clean or a correction factor greater than unity applied to the indicated current speeds. Presence of an anti-fouling aerosol similar to petroleum jelly does not effect performance significantly.

The "time constant" (time for 63% response to a step change) is nominally 1 second for acceleration and 2.5 seconds for deceleration, both taken above 0.2 knots for a speed change about equal to the mean speed. The response is better at higher speeds and deteriorates rapidly (longer time constant) as the current speed approaches zero.

The amount of influence of vertical motion on current meter indications seems to be proportional to the magnitude of the vertical component relative to the horizontal component. The experiments discussed in this report do not simulate wave action but it is tentatively concluded that significant (10% or better) variations in meter output will occur in the presence of vertical particle motions of 2 feet or more occurring with a period of 5 to 10 seconds in the presence of a 1/2 knot current. The Richardson meters may or may not be less susceptible to these motions than the meters tested.

XII. ACKNOWLEDGMENTS

The equipment and most of the data analysis and report preparation for the vertical motion part of these studies has been furnished by the Public Health Service. The main source of support for the rest of this work has been the Office of Naval Research under contract Nonr 2119(4) at the A. & M. College of Texas. The participation, guidance and encouragement of James M. Snodgrass has made much of this work possible and his support has also come from the Office of Naval Research under contract Nonr 2116(1) at the Scripps Institution of Oceanography. Donald J. Cretzler has also contributed to this work and has made available, through the Bissett-Berman Corporation, the tow tank facilities and considerable technical assistance.

J. I. McQuilken performed the tilt and vertical motion tow tank experiments. Mrs. Anita McAdams did the data analysis.

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APPENDIX A

SUMMARY OF STEADY STATE OUTPUT AVERAGES (IN REV./SEC.) FOR ROTORS CS-6 AND ST-5 TOWED WITH AXIS VERTICAL

	Rotor CS-6				Rotor ST-5			
Run No.	Rev. 6-10	Rev. 11-15	Rev. 16-20	Avg.	Rev. 6-10	Rev. 11-15	Rev. 16-20	Avg.
3	.0464	.0455	---	.046	.0346	---	---	.0346
5	.118	.1165	.115	.1165	.1057	.105	.103	.105
6	.331	.328	.330	.330	.308	.312	.3085	.3095
7	.501	.504	.498	.501	.505	.506	.505	.5053
8	.0835	.0827	.080	.0821	.0634	.0656	.0677	.0656
9	.2415	.244	.246	.244	.230	.2275	.233	.230
10	.3285	.329	.327	.328	.327	.326	.3225	.325
12	.328	---	---	.328	.325	---	---	.325
13	.517	.515	.517	.516	.484	.465	.467	.472
15	.0415	.0427	---	.0421	.0321	---	---	.0321
17	.473	---	---	.473	.434	---	---	.434

APPENDIX B

SUMMARY OF STEADY STATE OUTPUT AVERAGES
(in rev./sec.) FOR ROTOR CS-6 TOWED WITH AXIS TILTED

Run No.	Tilt Angle	Rev. 6-10	Rev. 11-15	Rev. 16-20	Avg.
19	-10°	0.1244	0.1250	0.1229	0.124
20	+10°	0.1370	0.1374	0.1390	0.138
21	-10°	0.946	0.941	0.946	0.944
22	+10°	1.070	1.087	1.090	1.082
23	-15°	0.1118	0.1117	0.1110	0.1115
24	+15°	0.1340	0.1351	0.1317	0.1335
25	-15°	0.895	0.904	0.898	0.899
26	+15°	1.015	1.008	1.031	1.018
27	-20°	0.0987	0.1028	0.1018	0.101
28	+20°	0.1184	0.1137	0.1193	0.117
30	+20°	0.946	0.938	0.932	0.938
31	-20°	0.838	0.822	0.821	0.827

APPENDIX C

SUMMARY OF STEADY STATE OUTPUT AVERAGES
(in rev./sec.) FOR ROTOR ST-5 TOWED WITH AXIS TILTED

Run No.	Tilt Angle	Rev. 6-10	Rev. 11-15	Rev. 16-20	Avg.
19	-10°	0.1177	0.1208	0.1190	0.119
20	+10°	0.1302	0.1297	0.1343	0.131
21	-10°	0.995	0.984	0.987	0.989
22	+10°	1.097	1.083	1.088	1.088
23	-15°	0.1145	0.1100	0.1107	0.1115
24	+15°	0.1220	0.1238	0.1240	0.123
25	-15°	0.941	0.914	0.920	0.925
26	+15°	1.050	1.024	1.035	1.036
27	-20°	0.1018	0.0960	0.1001	0.0995
28	+20°	0.118	0.1124	0.1113	0.112
30	+20°	0.966	0.961	0.982	0.969
31	-20°	0.890	0.895	0.879	0.888
50	-20°	0.1018	0.0990	0.0986	0.100
51	+20°	1.012	0.989	0.977	0.993
53	+30°	0.1043	0.1037	0.1061	0.1045
54	-30°	0.0880	0.0849	0.0860	0.0865
55	+30°	0.825	0.836	0.827	0.829
56	-30°	0.827	0.835	0.836	0.833

APPENDIX D

SUMMARY OF RESPONSE TEST RUNS FOR ROTOR CS-6, NOVEMBER 1962

Run No.	u_1 (kts.)	u_2 (kts.)	$\overline{u}$ (kts.)	Δu (kts.)
3	0	0.051	0.026	0.051
5	0	0.104	0.052	0.104
6	0	0.246	0.123	0.246
7	0	0.361	0.181	0.361
8	0	0.077	0.039	0.077
9	0	0.191	0.096	0.191
10	0	0.245	0.123	0.245
11	0	0.242	0.121	0.242
12	0	0.246	0.123	0.246
12	0.246	0.360	0.303	0.114
12	0.246	0.135	0.191	-0.111
13	0.372	0.136	0.254	-0.226
16	0.505	0.337	0.421	-0.168
16	0.337	0.171	0.254	-0.166
17	0.032	0.505	0.269	0.473
17	0.505	0.339	0.422	-0.166
17	0.339	0.172	0.255	-0.167
18	0.742	0.508	0.625	-0.234
18	0.508	0.172	0.340	-0.336

APPENDIX E

SPEEDS INDICATED BY ROTORS FOR CONSTANT SPEED RUNS IN THE PRESENCE OF VERTICAL OSCILLATION

					Rotor CS-6		Rotor ST-5	
Run No.	Osc. Period (sec.)	Osc. Height (ft.)	Record Length (sec.)	Carr. Speed (kts.)	Rev. Avg. (kts.)	Time Avg. (kts.)	Rev. Avg. (kts.)	Time Avg. (kts.)
32	20	2	100	0.116	0.106	0.105	0.117	0.116
33	15	2	75	0.116	0.109	-----	0.109	-----
36	5	2	25	0.735	0.580	-----	-----	-----
37	5.2	2	21.6	0.735	0.580	0.574	0.643	0.641
38	10	2	30	0.735	0.647	-----	0.709	-----
39	15	2	90	0.735	0.686	-----	0.686	-----
40	20	2	100	0.735	0.705	-----	0.741	-----
41	20	1	100	0.116	0.100	0.100	0.102	0.102
42	15	1	75	0.116	0.098	-----	0.099	-----
43	10	1	50	0.116	0.106	-----	0.113	-----
44	5	1	75	0.116	0.096	-----	0.099	-----
45	5	1	25	0.735	0.653	-----	0.689	-----
46	10	1	50	0.735	0.706	-----	0.738	-----
47	15	1	90	0.735	0.721	-----	0.698	-----
48	20	1	110	0.735	0.719	-----	0.744	-----

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